# Full Scale Testing of a Centrifugally Powered Pneumatic Deicing System for Helicopter Rotor Blades

Matthew Drury - Graduate Research Assistant, Aerospace Engineering
Dr. Joseph Szefi – President, Invercon
Dr. Jose Palacios – Assistant Professor, Aerospace Engineering

Funded by NASA LEARN NNX14AF54A

NASA Aeronautics Research Mission Directorate (ARMD)

2015 LEARN Technical Seminar

September 30, 2015

# Agenda

- Background and Motivation
- Objectives
- Prototype Designs
- Rotor Ice Testing Results
- Full Scale Blade Modifications
- Full Scale Testing Results
- Conclusions

# Introduction to Icing

**Aircraft icing is introduced by both its mission requirements and operation environments:**

- Urgent transportation
- Search and rescue
- Low altitude
- Low temperature
- High humidity, icing cloud possible


A rescue helicopter waiting to be rescued

**Unique features of helicopter icing:**

- Increased torque required to maintain RPM
- Excessive vibration due to blade imbalance
- Loss of control and maneuverability
- Loss of autorotation capability
- Ballistic impacts from ice shedding

**Ultimate goal of aircraft icing research: All weather aircraft**
**Need for fundamental research to:**

- **Improve and validate ice accretion tools**
- **Develop and evaluate ice protection systems and protective surfaces**
- **Develop facilities and testing procedures**

# Motivation – Electrothermal Deicing

- Only system qualified by the FAA and the DoD
- Heavy system (4 Blades 12,000 lbs Model: >160 lbs.)
- Does not allow for continuous application due to high power consumption

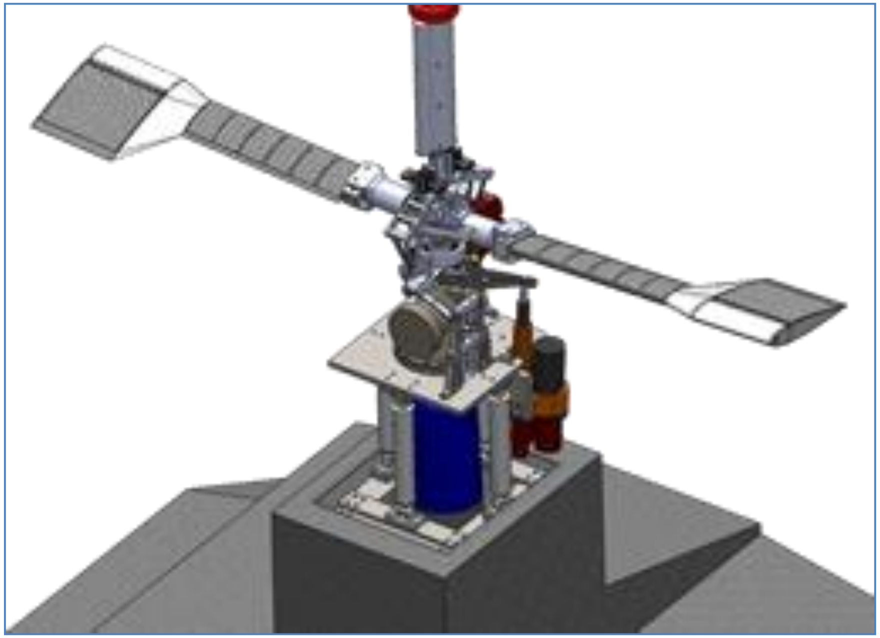
  (4 Blades, 12,000 lbs Vehicle: >20 KW, ~25 W/in$^2$)
- Allows ice accretion up to 0.3 in (10% Torque Increase)
- Melted ice may flow aft and refreeze further
- Difficult to integrate with polymer erosion-resistant materials

*ARMY HISS Icing Certification Testing*
*Ice Protection System (S-92$^{TM}$)*

**A low-power, non-thermal IPS is desired to have an impact on all-weather capabilities:**

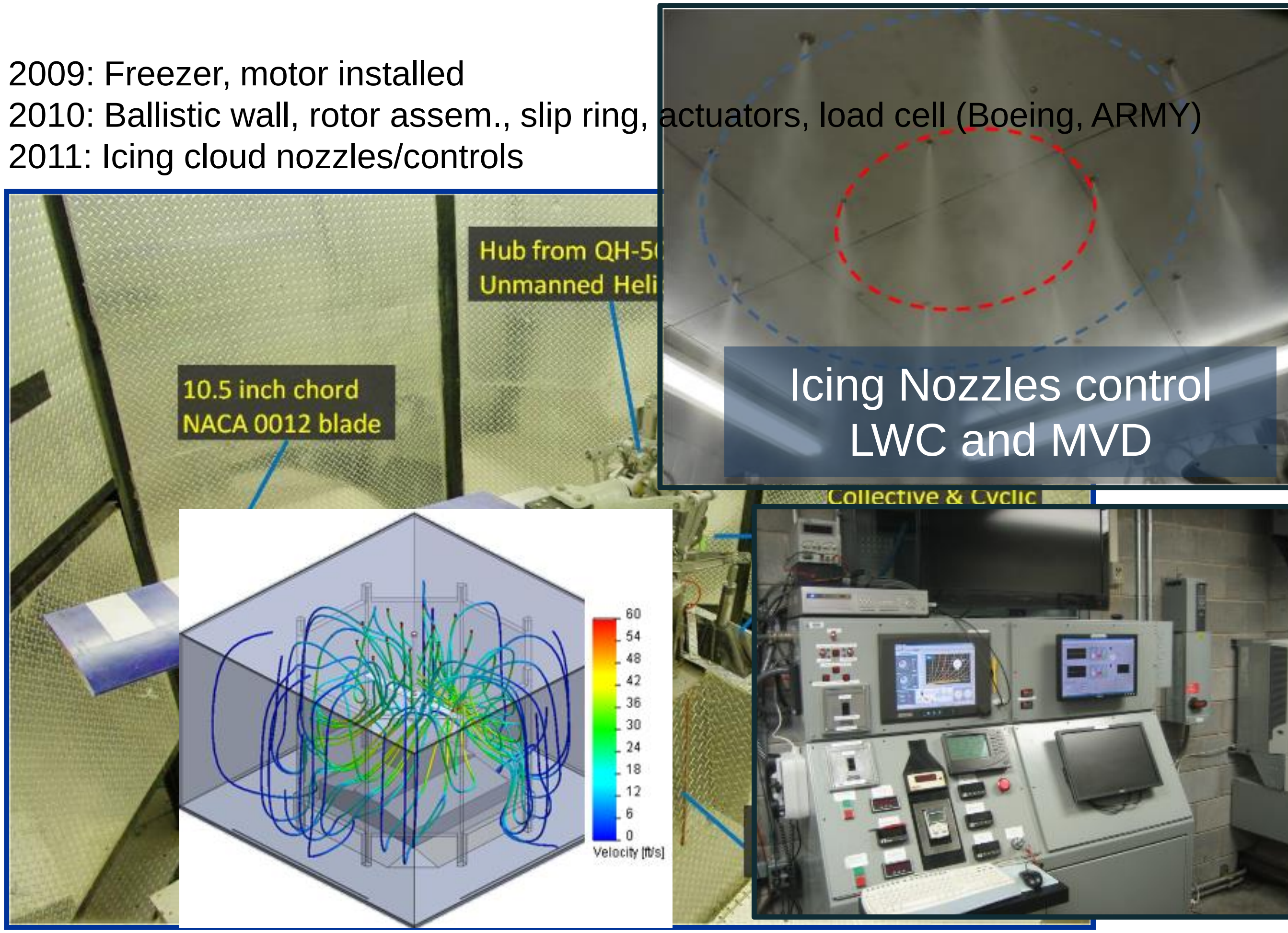
- **Compatibility with smaller vehicles**
- **Compatibility with polymer leading edges**

# Penn State AERTS Facility



# AERTS Facility Description

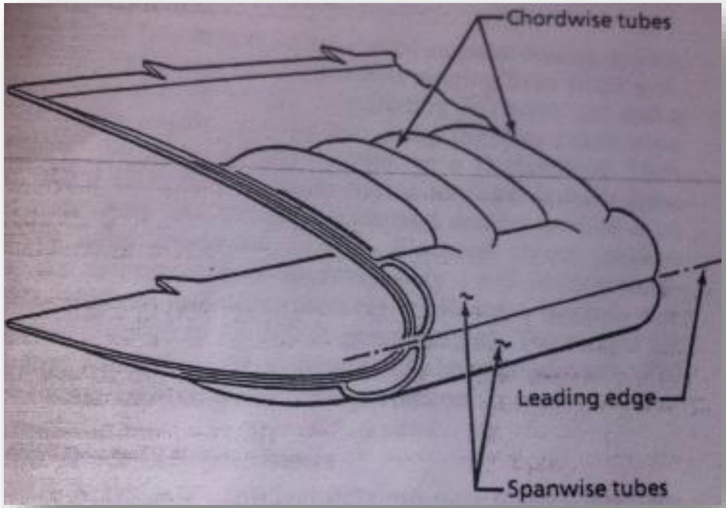
2009: Freezer, motor installed
2010: Ballistic wall, rotor assem., slip ring, actuators, load cell (Boeing, ARMY)
2011: Icing cloud nozzles/controls



# Background

- Pneumatic de-icing boots → used on fixed-wing aircraft for decades
- In the 80's, NASA and Goodrich attempted to develop **rotorcraft** de-icing boots
- Boots were successful in de-icing rotor blades, several problems were identified:
    1) Complicated pneumatic slip-ring transferred engine bleed air out to rotating frame
    2) Erosion of polymer boots
    3) Altered airfoil shape led to rotor performance degradation
- These problems were technology development barriers

Fig. 1. Photo JUH-1 test helicopter



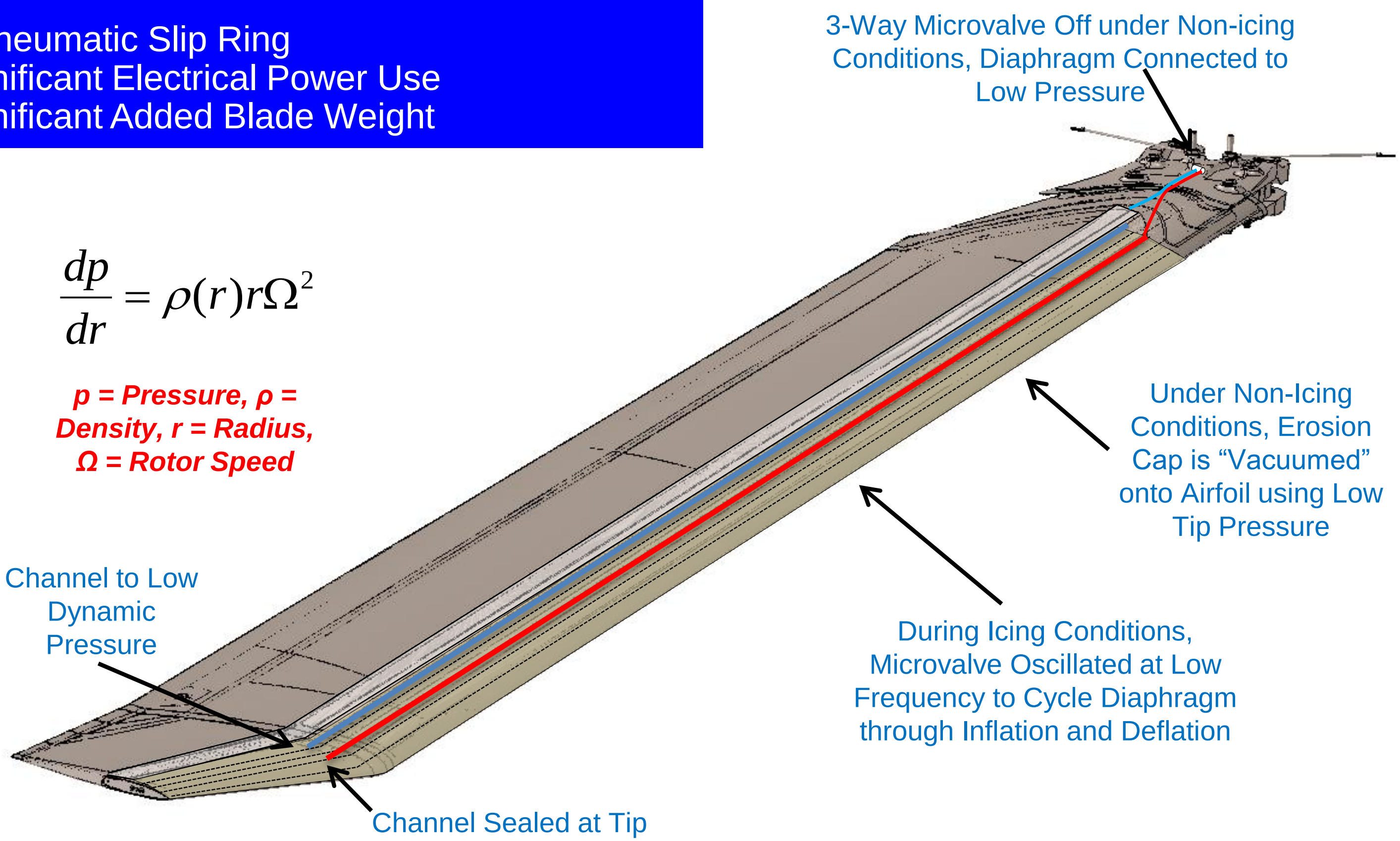
# Centrifugally Powered Pneumatic De-Icing Concept

Goal: Surface De-Icing Treatment can be Retrofitted to Existing Blades

- No Pneumatic Slip Ring
- Insignificant Electrical Power Use
- Insignificant Added Blade Weight

$$\frac{dp}{dr} = \rho(r) r \Omega^2$$

***p = Pressure, ρ = Density, r = Radius, Ω = Rotor Speed***




***Patented by Invercon LLC:***
***"Pneumatic Actuator System for a Rotating Blade"*, EFS ID: 9369871, Application Number:13020333**

# On-Blade Pressure Generation Testing

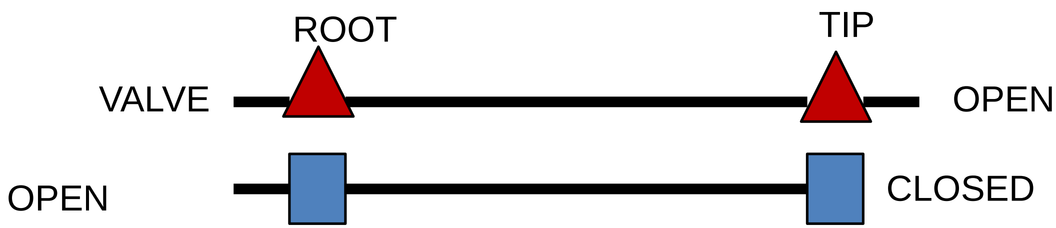
***Pressure Drop in Full-Scale Rotor***
**Experimentally Demonstrated: 7.5 *PSI***

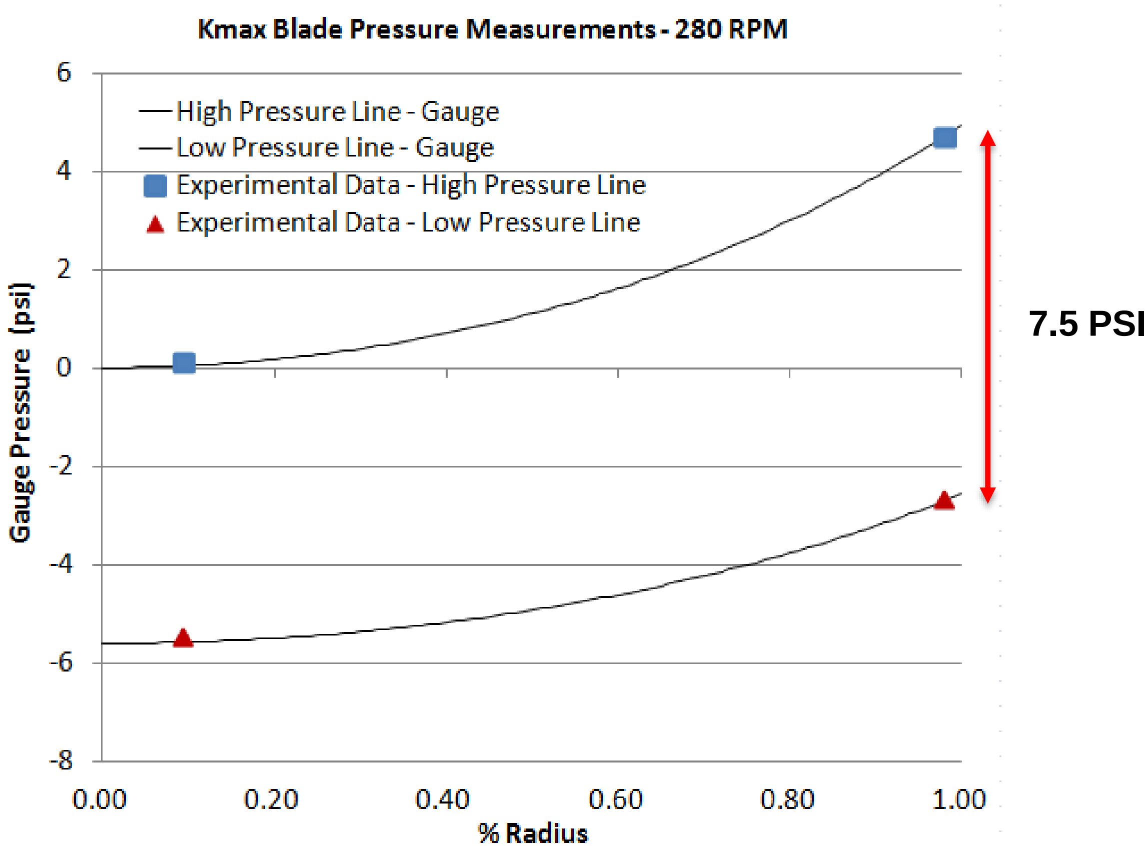
2 Pressure Sensors on Root

2 Pressure Sensors on Tip

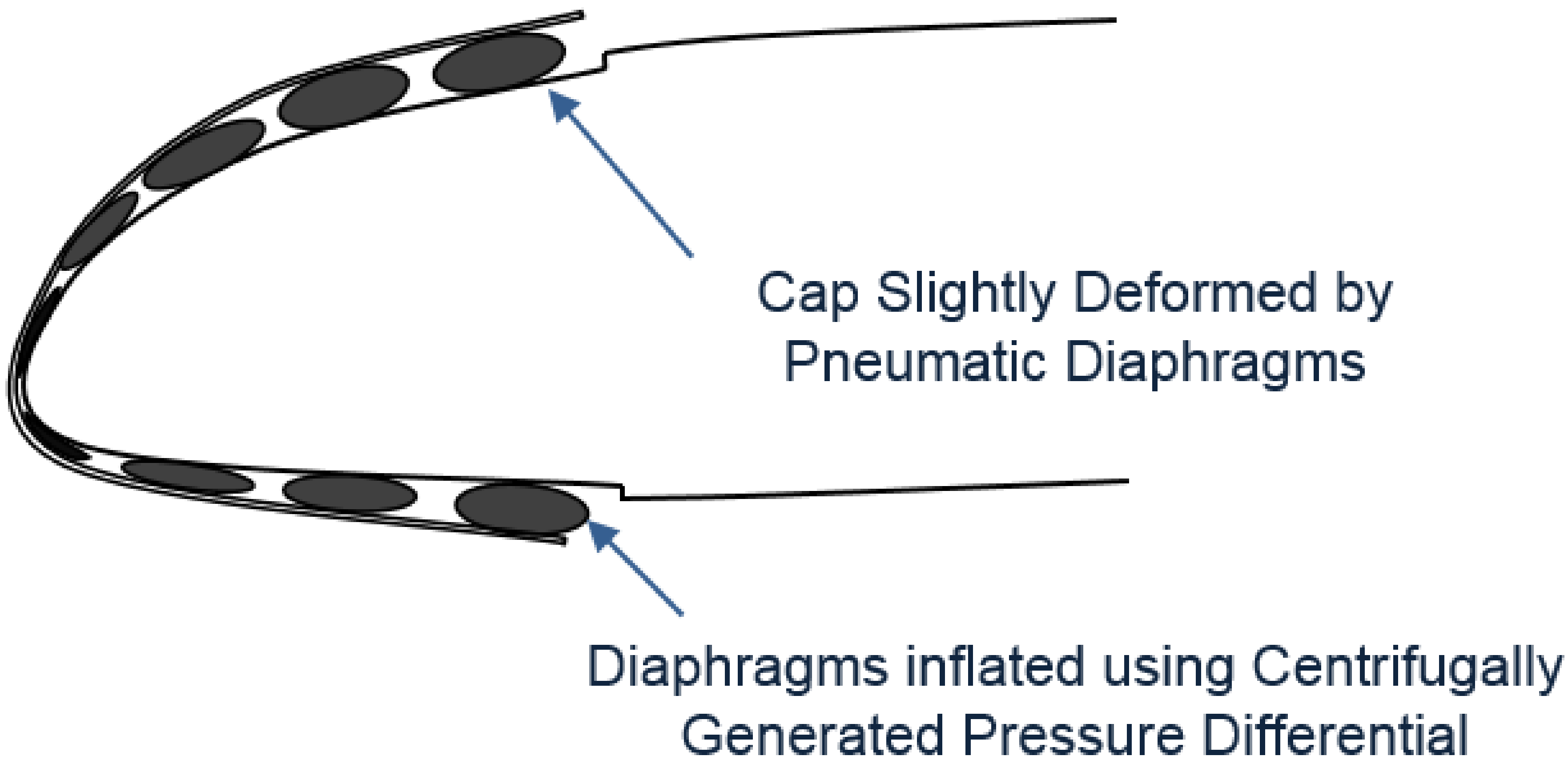

280 RPM, 24 ft. Radius Rotor

# On-Blade Pressure Generation Testing



# Prior Work – Prototype I



# Agenda

- Background and Motivation
- Objectives
- Prototype Designs
- Rotor Ice Testing Results
- Full Scale Blade Modifications
- Full Scale Testing Results
- Conclusions

# Objectives

1. Design a centrifugally powered pneumatic deicing system without the use of inflatable rubberized structures.
2. Evaluate the new system design under rotor icing conditions at the AERTS facility.
3. Integration of the selected system to the outer tip region of a full-scale K-MAX rotor blade.
4. Design and testing of a portable icing cloud generator.
5. Rotor ice testing of the full-scale prototype.

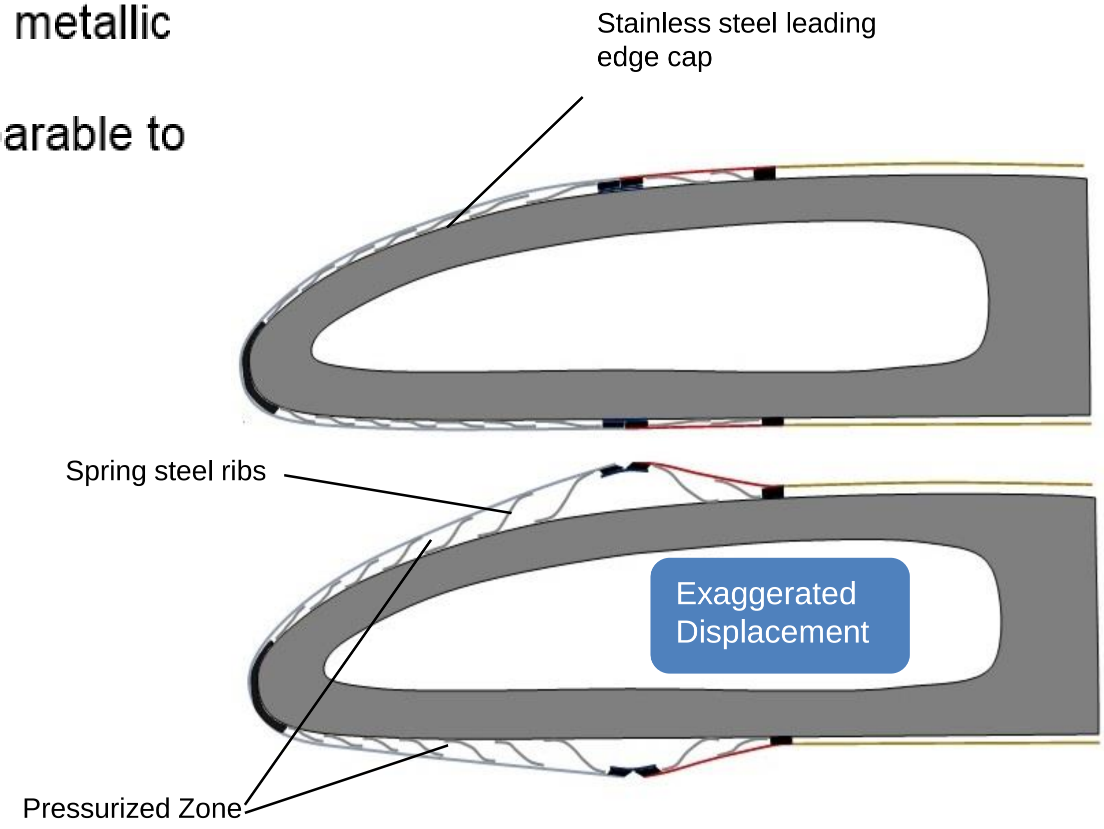
# Agenda

- Background and Motivation
- Objectives
- Prototype Designs
- Rotor Ice Testing Results
- Full Scale Blade Modifications
- Full Scale Testing Results
- Conclusions

# Pneumatic De-Icing Prototype II Design

**Goals:**

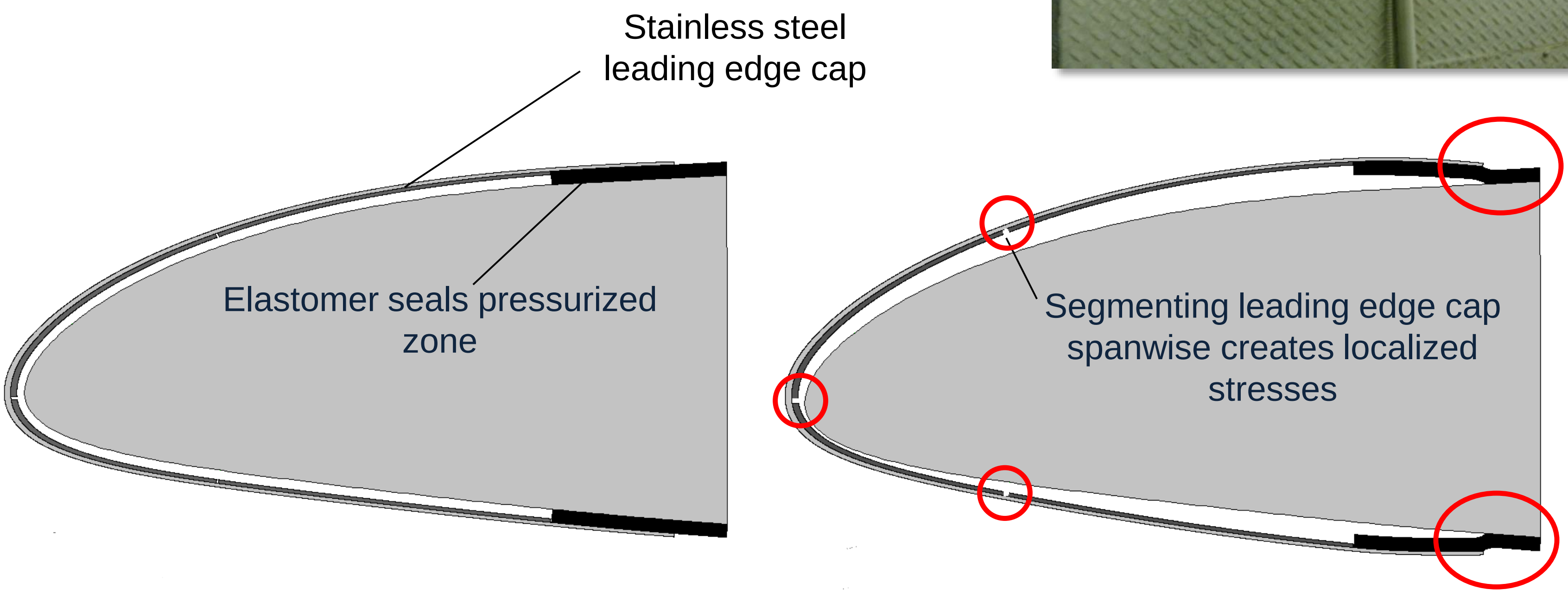
1. Replace neoprene bags with metallic pressurized zones.
2. Total system thickness comparable to existing leading edge caps.



# Pneumatic De-Icing Prototype III Design

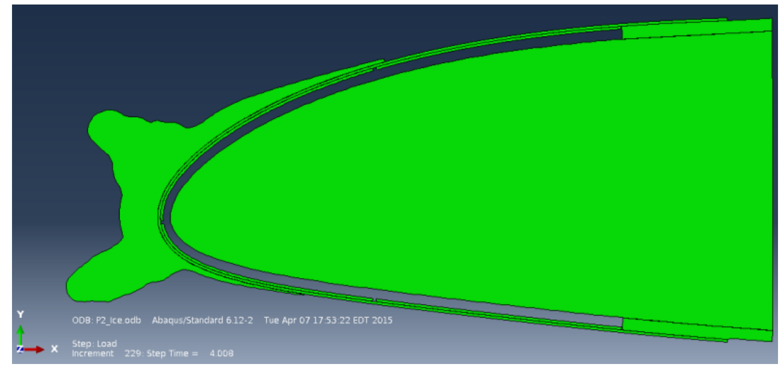
**Goals:**

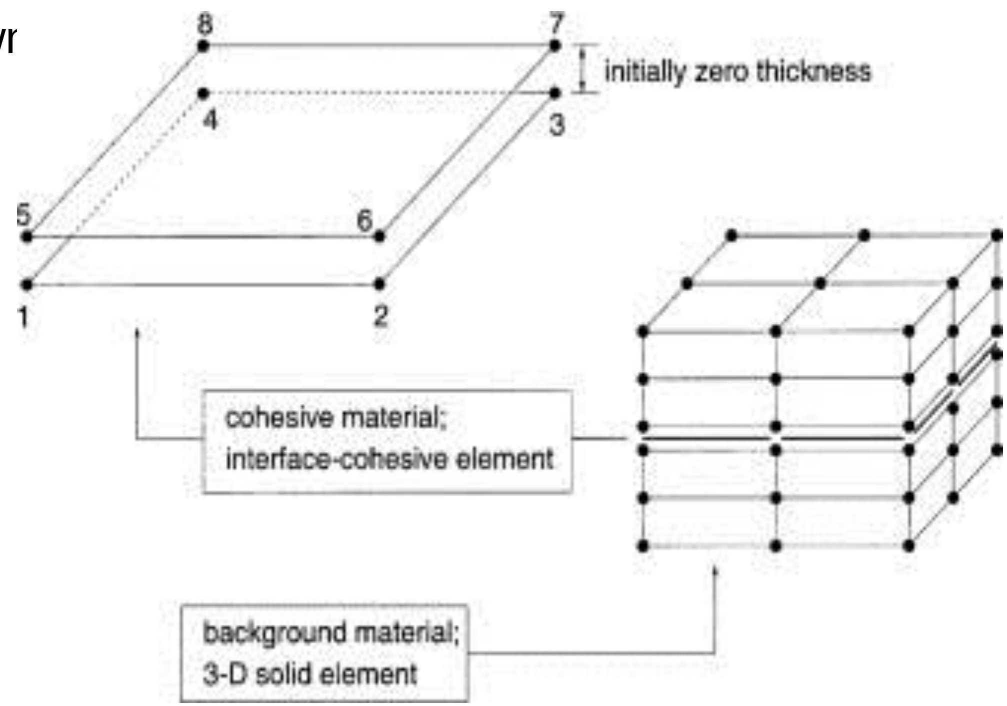
1. Reduce aerodynamic penalty caused by trailing edge jump
2. Increase transverse shear stresses at desired chord locations



# Sample Ice Delamination Prediction – Cohesive Interactions

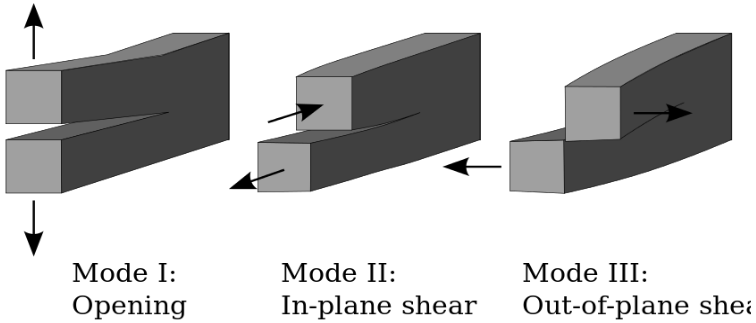
- Cohesive interaction used to “attach” ice to leading edge cap in Abaqus
- Two types of cohesive interactions defined in Abaqus:
  1. Cohesive elements
  2. Cohesive surfaces
- Cohesive surfaces have been shown to be best for ice/leading edge interface
- Damage models used to predicted when this cohesive bond fails

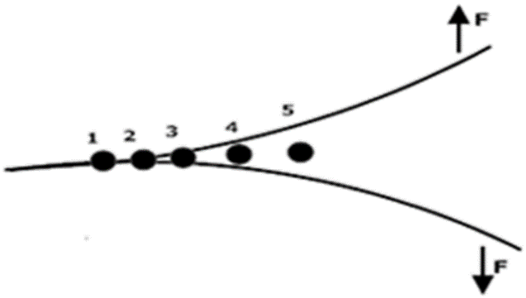


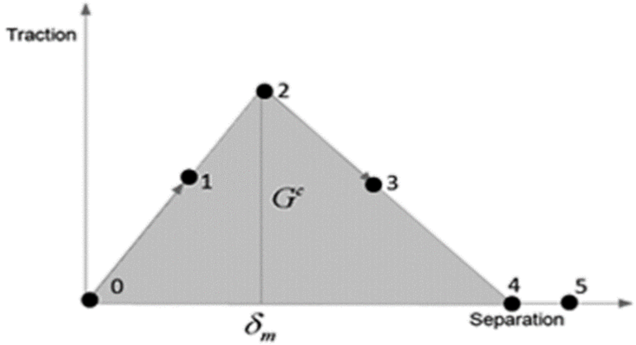



# Sample Ice Delamination Prediction – Damage Modeling

- Derived from fracture mechanics
- Pneumatic deicing system creates mixed mode stresses when pressurized
  - Combination of peel and shear stresses



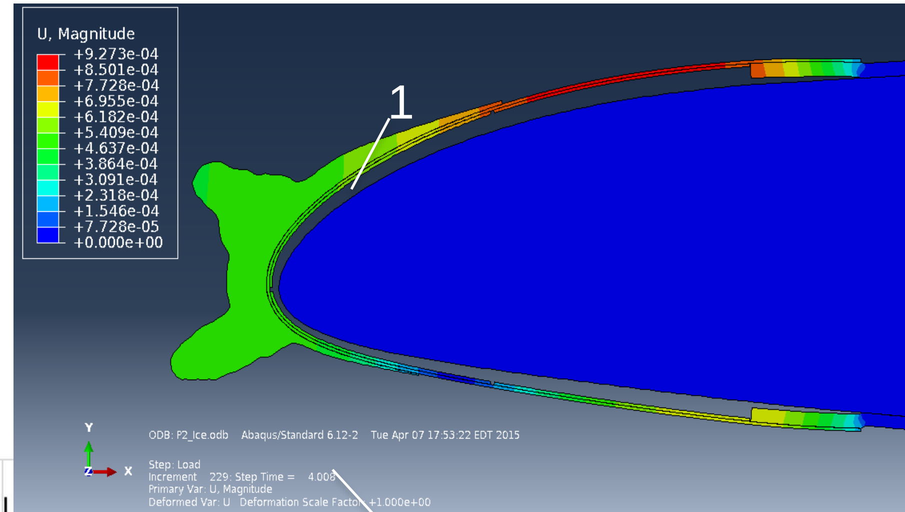



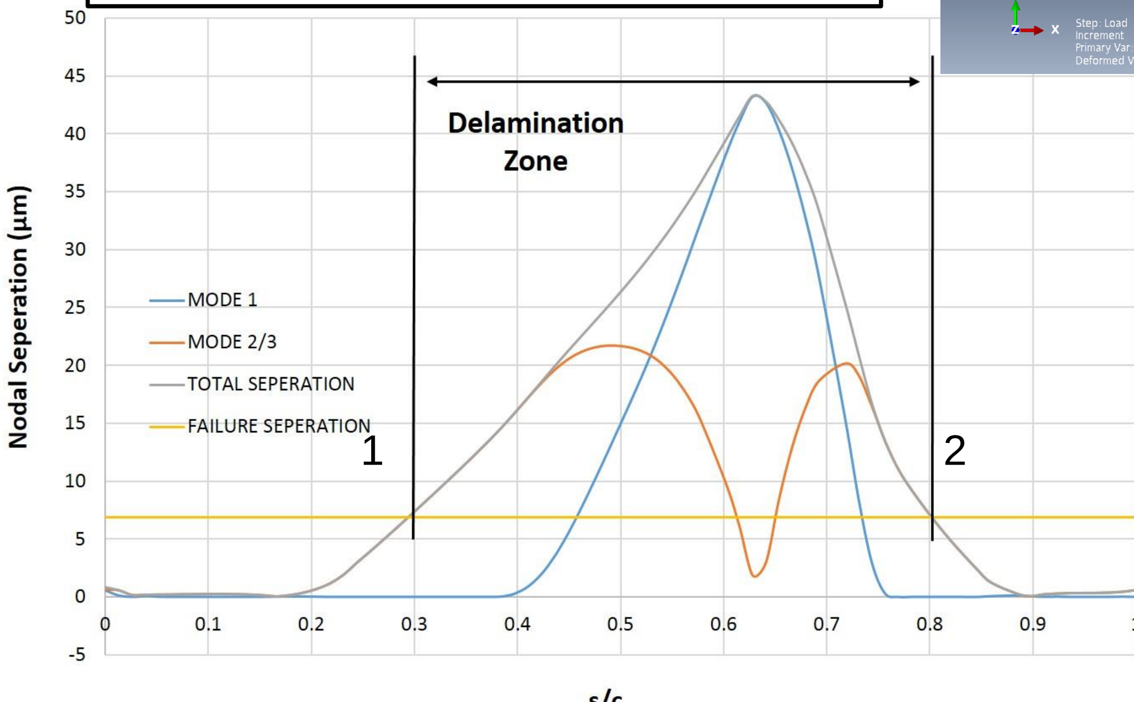




- Traction separation laws used to model cohesive damage
- Damage and cohesive parameters were measured in Phase I

# Sample Ice Delamination Prediction – Blade Tip

- Ice shape geometry created with LEWICE
- Abaqus cohesive zone methods predict interfacial delamination
- Centrifugal forces and aerodynamic pressures not included in analysis
- Ice delamination predictions using cohesive models used to guide system design

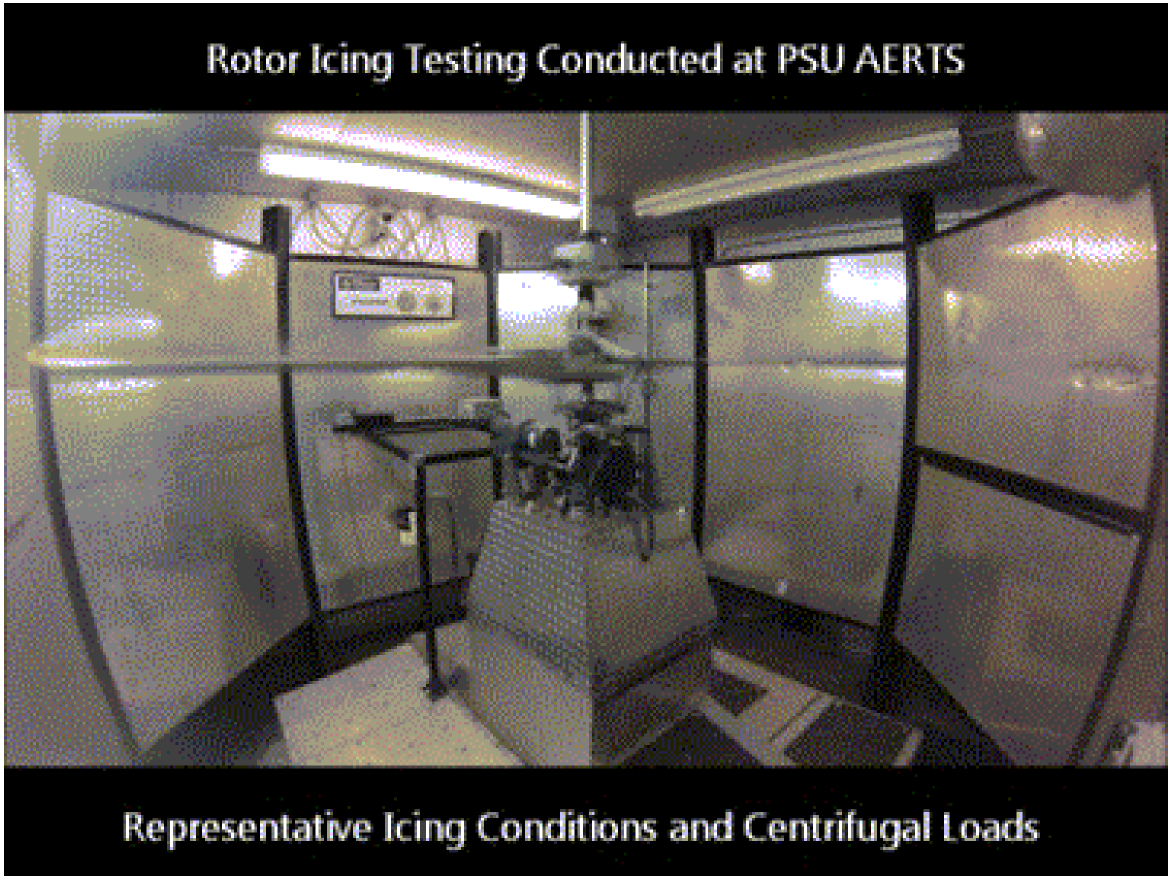


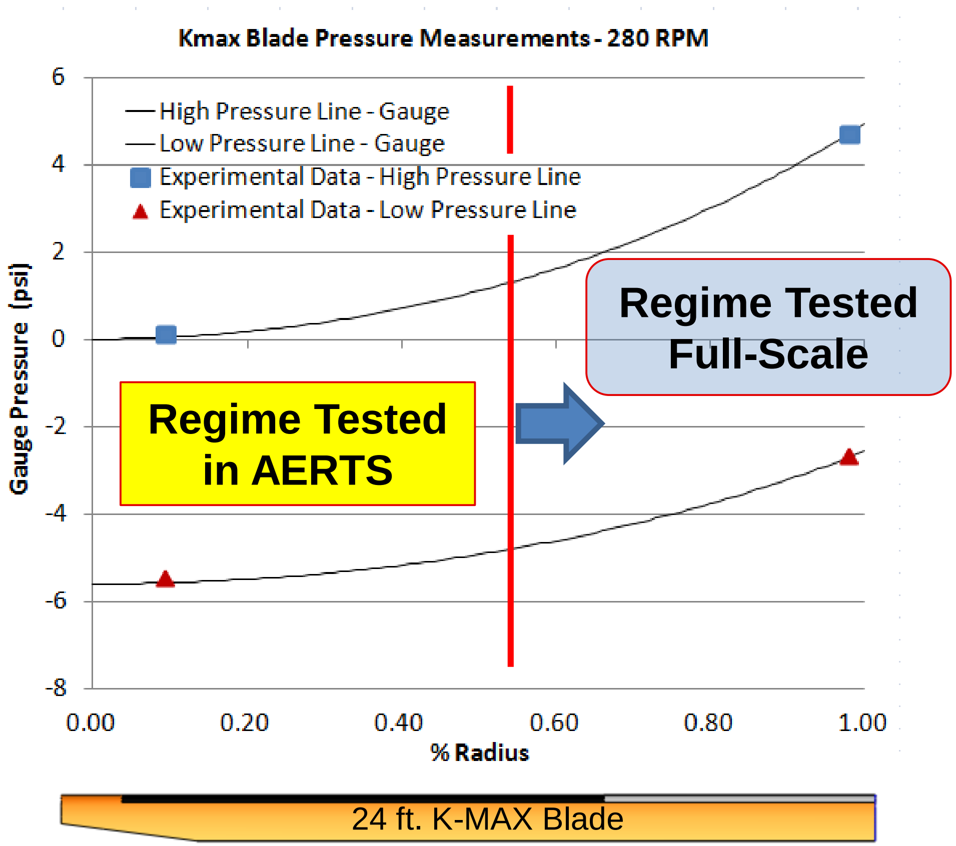
# Agenda

- Background and Motivation
- Objectives
- Prototype Designs
- Rotor Ice Testing Results
- Full Scale Blade Modifications
- Full Scale Testing Results
- Conclusions

# Rotor Ice Testing



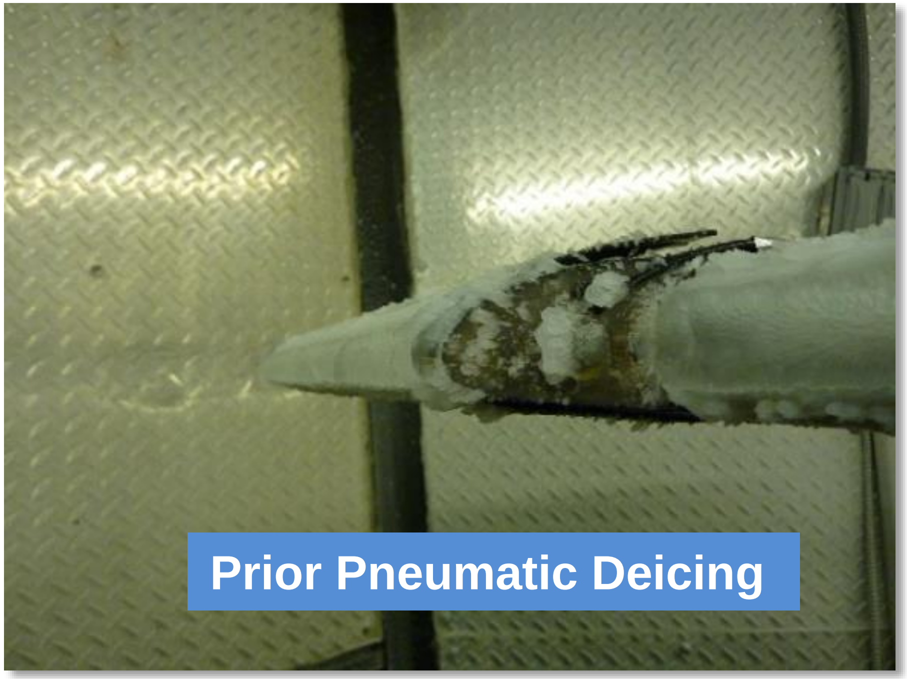
# Prototype Ice Testing – Full Scale Representation

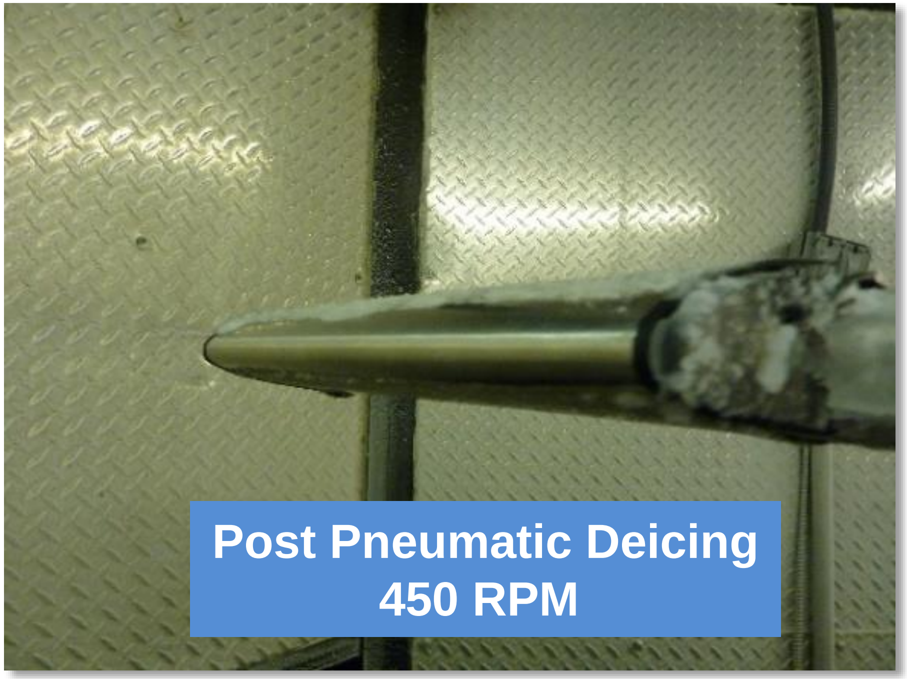



**Test Method:**
- Characterize prototype performance for input pressures produced along a 24 ft. blade
- Centrifugal loads representative of K-MAX 0.5R at 280 RPM
  → Conservative approach

# Rotor Ice Test Results – Prototype II

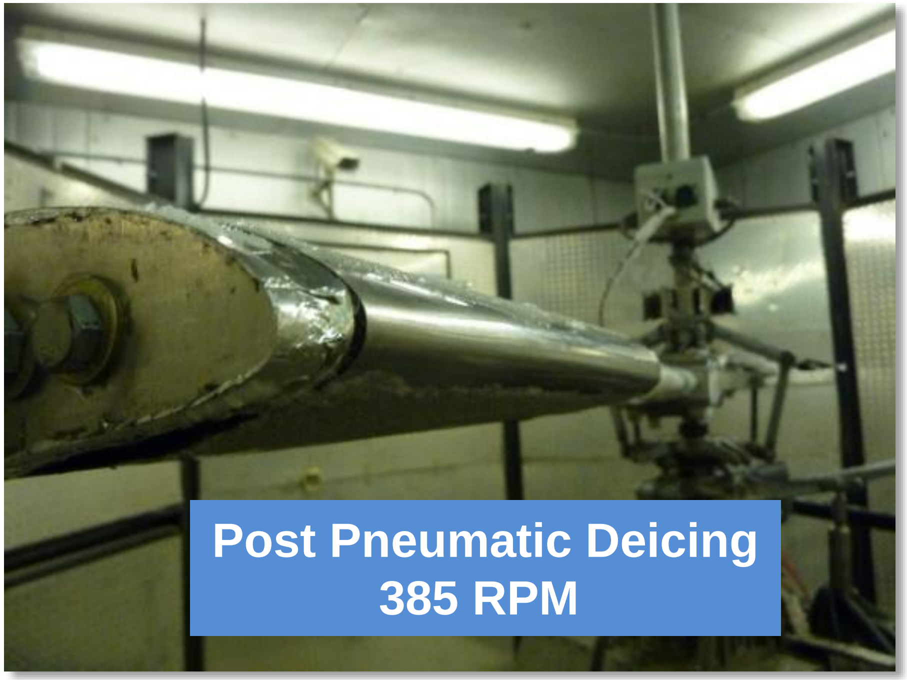
Pressures reproduced using pneumatic slip-ring



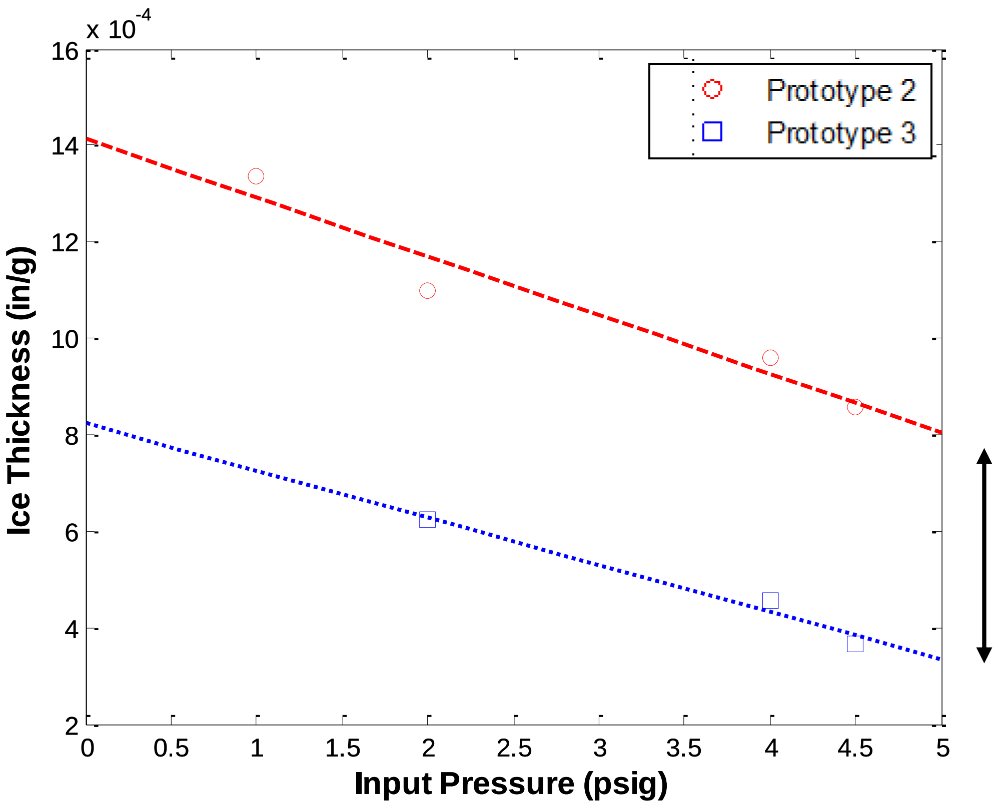



# Rotor Ice Test Results – Prototype III

Pressures reproduced using pneumatic slip-ring

# Rotor Ice Test Results - Prototype Performance



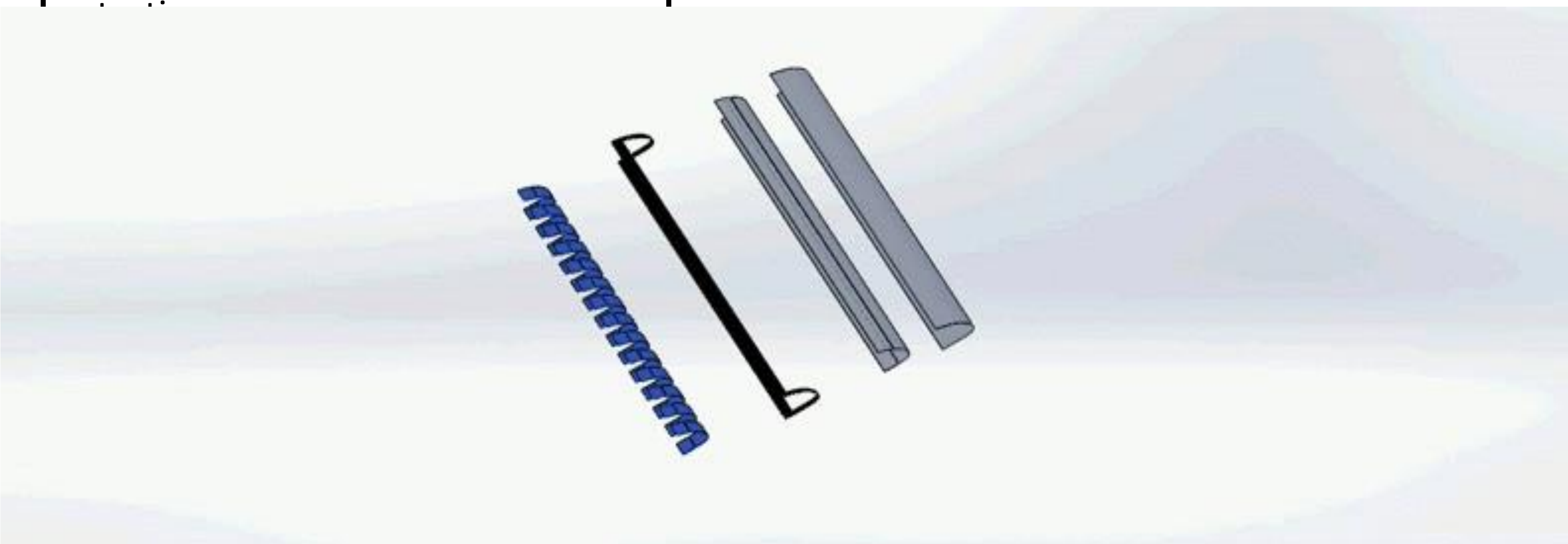

- **Increased input pressure → delaminate smaller ice thicknesses**
- **58% decrease in ice thickness for delamination from prototype II to prototype III**

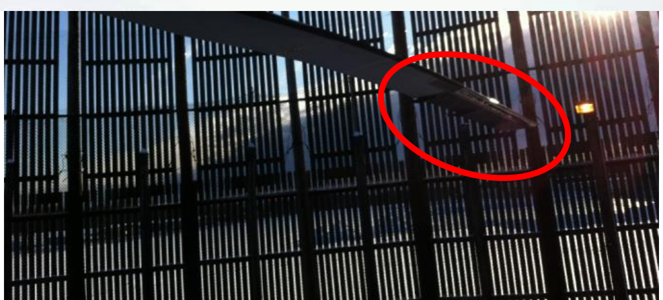
# Agenda

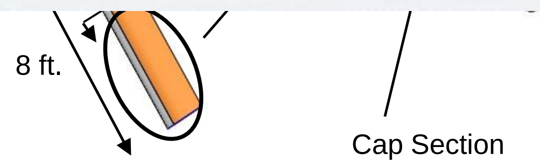
- Background and Motivation
- Objectives
- Prototype Designs
- Rotor Ice Testing Results
- Full Scale Blade Modifications
- Full Scale Testing Results
- Conclusions

# Full Scale Blade Modifications

- Prototype II selected for full scale





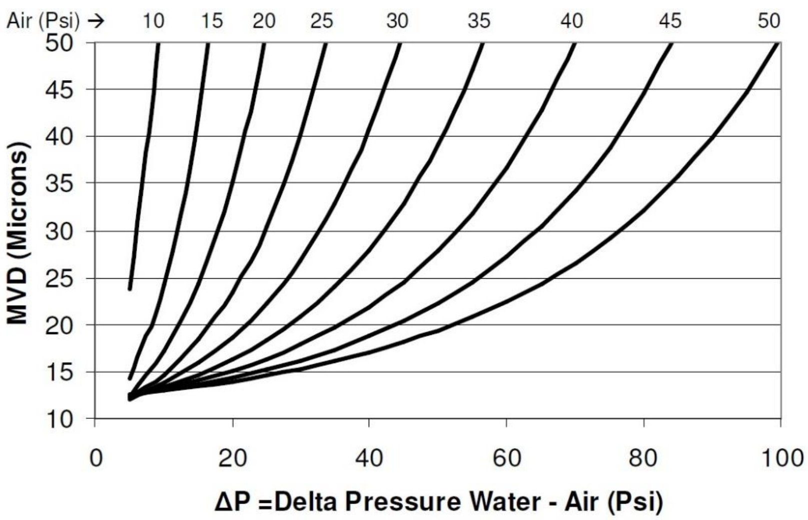


# Agenda

- Background and Motivation
- Objectives
- Prototype Designs
- Rotor Ice Testing Results
- Full Scale Blade Modifications
- Full Scale Testing Results
- Conclusions

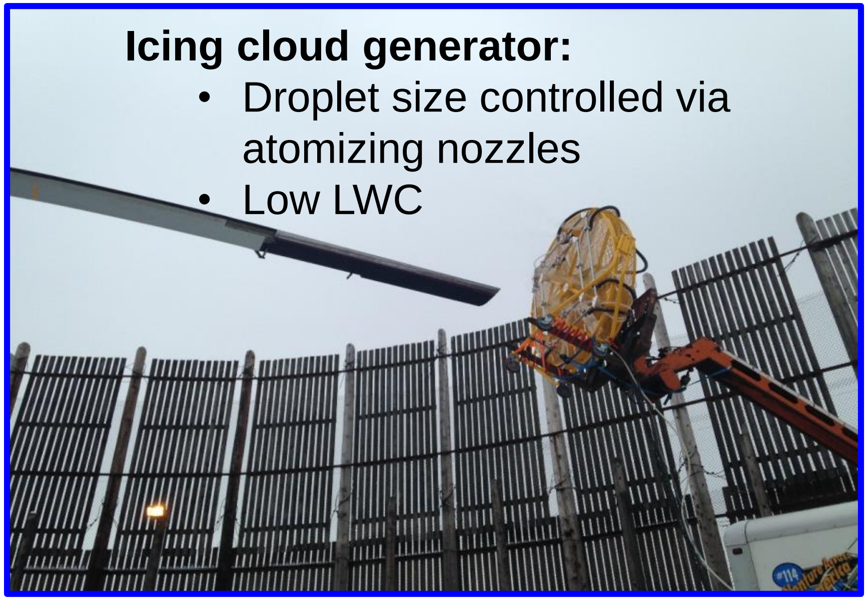
# Icing Cloud Generator

- NASA Standard icing nozzles produce an icing cloud
- Water droplet size controlled via input air and water pressures
- Controllable within FAR 25/29 icing envelop

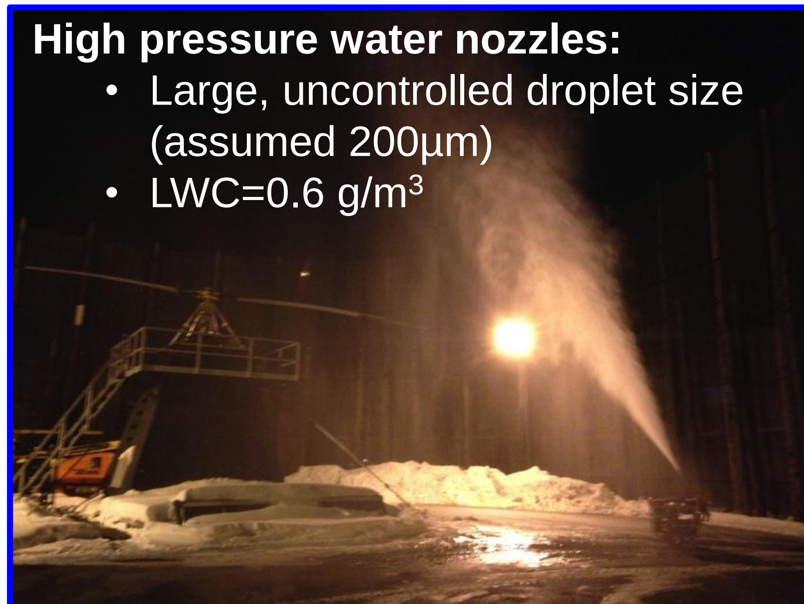



# Full Scale Icing Test - Icing Cloud

**Icing cloud generator:**
- Droplet size controlled via atomizing nozzles
- Low LWC



**High pressure water nozzles:**
- Large, uncontrolled droplet size (assumed 200µm)
- LWC=0.6 g/m$^3$



# Full Scale Icing Test Method

De

Sp

I
ac

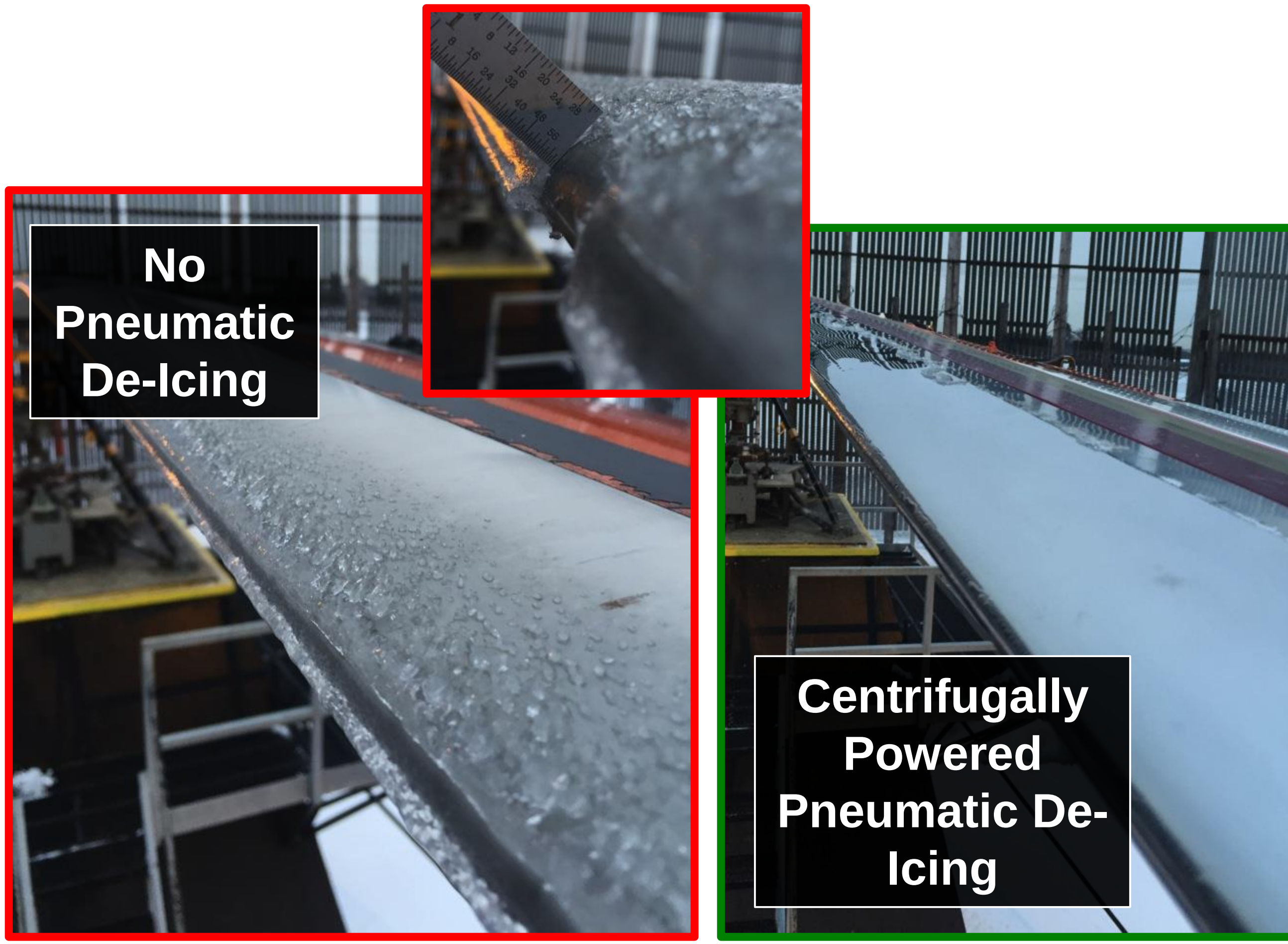
Icin


Icing cloud OFF

Maintain rotor speed

# Full Scale Icing Test Results

- Successful shedding of 8 ft. tip region (270 RPM)
- Max ice thickness of 0.08 in. successfully shed
- Temperatures from -10° C to -15° C tested
- Low power consumption (~1 W)



# Conclusions

1. Full-scale centrifugally powered pneumatic de-icing tested on a full-scale rotor blade
2. The de-icing system consumes virtually no power (~1 W)
3. Capability of centrifugal forces to create pneumatic pressures to debond ice demonstrated
4. De-icing system weight is comparable to that of existing erosion caps.
5. Minimum ice thickness is a fraction of that required by electro-thermal systems (32% of typical electrothermal ice accretion)

# Questions?